

MONITORING THE VARIABILITY OF  
ACTIVE GALACTIC NUCLEI FROM  
A SPACE-BASED PLATFORM

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## 1. INTRODUCTION

Active galactic nuclei (AGNs) are among the most luminous detected sources in every waveband in which they have been observed. Their bolometric luminosities are typically in the range  $10^{11-14} L_{\odot}$ . However, the mechanism by which the emitted energy is generated is not yet understood. The nearly 30-year-old paradigm is that the energy is produced via thermal viscosity in an accretion disk surrounding a supermassive (typically  $\gtrsim 10^7 M_{\odot}$ ) black hole. While gravity accounts for most of the energy production, magnetic fields are also thought to play a role in at least some AGNs by collimating a relativistic outflow of radio-emitting plasma. The accretion-disk hypothesis remains unproven because the expected signatures of the process are somewhat ambiguous and the models are not well-constrained by the observations. However, it is increasingly recognized that continuum variability provides one of the most direct probes of the energy-generation process. AGNs are known to vary dramatically across the entire observable electromagnetic spectrum, from  $\gamma$ -ray to radio energies, and it is only relatively recently that we have begun to exploit the variability characteristics of AGNs to probe the central regions.

For the purposes of this discussion, we will distinguish between two types of AGN, "normal AGNs" and "blazars," since the variability characteristics of the two types are quite different. Current thinking, as embodied in what are referred to as "unified models" (Antonucci 1993), holds that the apparent difference between the two types is due only to the aspect angle at which they are observed: blazars are simply AGNs that are observed along or very close to the radio axis so the detected flux is dominated by the relativistically beamed nonthermal radiation (synchrotron self-Compton) that arises in the radio jets. In the case of normal AGNs (Seyfert galaxies and non-beamed quasars), virtually all of the emission between the satellite

ultraviolet and the submillimeter is ascribed to thermal processes. The spectral energy distribution of normal AGNs shows a broad peak, the “big blue bump” (BBB) rising shortward of  $\sim 4000 \text{ \AA}$  and dropping off at energies less than  $\sim 1 \text{ keV}$  (there is debate as to whether the BBB extends into the soft X-ray band), which is usually supposed to be the signature of the accretion disk (Shields 1978; Malkan & Sargent 1982). In this scenario, UV/optical continuum variability is ascribed to accretion-disk instabilities (lower-amplitude, short-time scale variations) and to changes in the mass accretion rate (larger amplitude variations over longer time scales). However, it can also be argued that the BBB is due to optically thin bremsstrahlung rather than optically thick thermal emission (e.g., Barvainis 1993); this is more of a phenomenological argument, since the driving mechanism has not been identified. In principle, detailed observations of continuum variability, even in a single waveband, can provide a constraint on the physical mechanisms that might be at work in either optically thick or optically thin models.

In the case of blazars, continuum variability time scales and observed source brightness temperatures provide a strong constraint on the Doppler-beaming factors and thus yield strong lower limits on the source energetics.

## 2. PREVIOUS OBSERVATIONS

There have been few sustained programs to study systematically UV/optical variability in AGNs. The longest running program of which we are aware is the program of photographic photometry which has been undertaken by A.G. Smith and collaborators at the University of Florida for about two decades. The use of photographic detectors limits the accuracy of the photometry to  $\sim 10\%$ , which is adequate for studying the large amplitude variations (often more than a magnitude) seen in blazars, but of less utility for normal AGNs, where the rms variability over a year is typically only around 30%. Moreover, the temporal coverage that can be achieved at an inferior ground-based site is not sufficient to resolve the most rapid variations for either blazars or normal AGNs.

Until a few years ago, very little was known about the continuum variability characteristics of normal AGNs. This situation has changed on account of multi-wavelength emission-line reverberation mapping experiments that have been carried out with *IUE*, *HST*, and ground-based telescopes. The optical continuum light curve for the best observed normal AGN, NGC 5548, is shown in Fig. 1. Only a handful of normal AGNs have been observed in any detail, and in many cases they have been *preselected* based on earlier observations that showed they varied with amplitudes and time scales suitable for reverberation mapping experiments. Any generalizations based on existing results are thus highly suspect since it is not known how representative these highly variable sources may be of AGNs as a class. Furthermore, even the

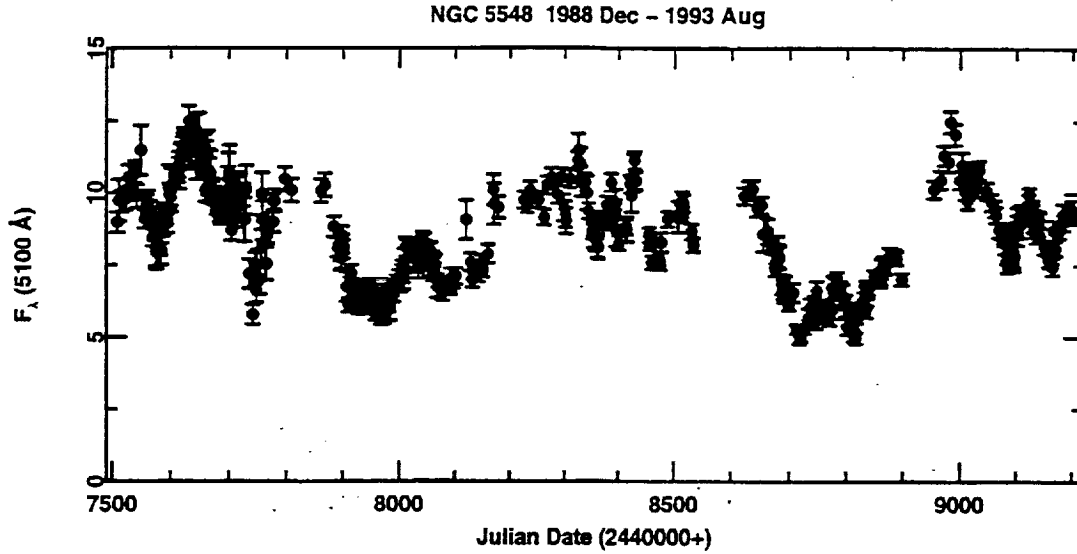


Figure 1: Optical continuum (5100 Å) light curves from the International AGN Watch monitoring of the Seyfert 1 galaxy NGC 5548. Fluxes (in the rest frame NGC 5548) are in units of  $10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$ . The average interval between observations is approximately 3 days and the typical error level is about 4%. Measurements from Peterson (1994) and unpublished International AGN Watch data.

best available variability data suffer from limited temporal coverage: ground-based coverage tends to be irregular due to telescope scheduling difficulties and unpredictable weather, and space-based coverage is usually limited in duration by solar proximity or spacecraft positive-power constraints. The most complete space-based programs (typically with time resolution of a few days) have run only about eight months (Clavel et al. 1991; Reichert et al. 1994). A program of continuous monitoring of NGC 4151, with time resolution of about 90 minutes, is scheduled for early December 1993, but the continuous coverage will last less than 10 days.

Another phenomenon that has received some attention over the past few years is that of *microvariability*, small amplitude ( $\gtrsim 0.1 \text{ mag}$ ) UV/optical variations which occur in blazars on time scales of hours. The best observations to date are those of BL Lac object PKS 2155–304 which were obtained in a massive campaign in 1991 (Urry et al. 1993).

Some of the existing data for both blazars and normal AGNs *suggest* the existence of periodic or quasi-period variability, indicative of the possible importance of orbital motion. The evidence for any periodicities is *very* marginal because the time series of observations are too short. Nevertheless, it is important to search for characteristic time scales because of the implications that their existence (or nonexistence) would

have for our understanding of the AGN phenomenon.

The fluctuation power density spectrum, or PDS (a measure of variability power as a function of temporal frequency), is of great potential use if both high enough and low enough temporal frequencies are explored. A PDS determined from UV/optical variability has been published for a normal AGN in only one case, NGC 5548, based on data obtained as part of the *IUE* monitoring campaign of 1988–89 (Krolik et al. 1991). These data show that the PDS is relatively steep ( $P(f) \propto f^{-(2-3)}$ ), but the dynamic range over which the PDS is measured is only a factor of  $\sim 4$ , in the frequency range  $(120 \text{ days})^{-1}$  to around  $(30 \text{ days})^{-1}$ . This range is insufficient to detect turnovers in the power spectrum at either the high or low frequency end.

It should also be mentioned that on-going searches for MACHOs will provide data that can be used to examine continuum variability in a large number of AGNs. Both the potential number of AGNs that can be studied and the duration of the experiment are comparable to what is envisaged for the FRESIP mission, but by comparison the MACHO survey data will be of much lower signal-to-noise ratio (a factor of about 10 lower at the faint end, where most of the AGNs will be detected), and the data will be more irregularly sampled on account of interruptions due to weather and seasonal gaps.

### 3. MONITORING AGN VARIABILITY WITH FRESIP

#### 3.1. Science Goals

A space-based observing platform such as FRESIP that is designed to carry out a multiyear monitoring program on a large number of sources in a fixed field affords an unprecedented opportunity to study AGN continuum variability. At least two very general questions can be addressed:

1. *Are there characteristic time scales or power density spectra for AGN variability?* With long, evenly sampled time series, that can *only* be obtained with space-based telescopes, it will be possible to search for characteristic frequencies and to determine the power density spectra of AGN variability with much greater confidence than has been done in the past. The temporal frequencies for sources observed with the FRESIP telescope in principle extend from  $\sim (3 \text{ year})^{-1}$  to  $\sim (0.1 \text{ day})^{-1}$ , i.e., a dynamic range of  $7 \times 10^4$ .
2. *As a class, how do AGNs vary?* Surprisingly, there is virtually *no* reliable information on the statistics of AGN variability – there is insufficient existing information to answer simple questions such as what fraction of AGNs with luminosity  $L$  will vary by an amount larger than  $\delta L$  in some time  $\Delta t$ ? These sorts of considerations are crucial in understanding correlations involving AGN

luminosities, such as the Hubble diagram and the Baldwin effect. The existing data, usually based only a handful of observations of several sources, are consistent with virtually *all* AGNs varying detectably on time scales less than a year or so. Only a very few AGNs have been studied in detail, and those sources have often been selected for study *because of* their variability.

### 3.2. Technical Feasibility

In this section, we make a statistical estimate of how many AGNs one might be able to monitor with the baseline FRESIP design in a mode that is compatible with the primary science objectives of the mission. Note that many of the considerations addressed here apply generally to faint objects that might be observed with FRESIP, such as cataclysmic variables (cf. Howell, these proceedings).

We note the following specific points:

1. We will assume that the minimum acceptable signal-to-noise ratio ( $S/N$ ) = 100; this significantly exceeds the quality of data that currently exist and there is no obvious reason to push for much higher  $S/N$  to detect variability that is energetically not especially important. While lower  $S/N$  data would still have some value, they would not be markedly better than what one could obtain from the ground. The advantage of FRESIP's rapid time resolution would be lost by compromising further on the allowable  $S/N$ .
2. We will assume that the minimum temporal resolution is 1 hour. On the basis of what is known about AGN variability, this is more than sufficient, even for microvariability studies. For virtually all AGNs, the FRESIP telescope will operate in the background-dominated regime so further improvement in signal-to-noise ratio  $S/N$  can be obtained by summing over many hours, in which case  $S/N \propto t^{1/2}$ , where  $t$  is the total exposure time.
3. The FRESIP field (at Galactic coordinates  $\ell = 90^\circ$ ,  $b = 15^\circ$ ) is not optimal for extragalactic studies as the foreground extinction is not negligible and quite variable across the field (in the range  $0.1 \lesssim E_{B-V} \lesssim 0.5$ , with a typical value of  $E_{B-V} \approx 0.2$ ; Burstein & Heiles 1982), but nevertheless usable. The sky background is assumed to be quite low ( $\mu_V \approx 22$  mag arcsec $^{-2}$ ) since the field center is near the north ecliptic pole (avoiding much of the zodiacal light contribution) and not too close to the Galactic equator (where the background due to unresolved stars becomes important).

4. For parameters that are likely to change somewhat in the final design, we assume  $24\ \mu\text{m}$  pixels, a pixel scale of  $2''.6\ \text{pix}^{-1}$ , and that each image will cover 9 pixels. This translates to a field of view of about  $7''.4$ . We will assume that the read-out noise per subintegration is  $50\ \text{e}^- \text{pix}^{-1}$ .

Given the baseline assumptions about the telescope/detector system (i.e., 1-m effective aperture, 80% throughput, detector quantum efficiency of 50% over the range 450 – 850 nm, and 2.3 sec subintegrations, we find that the read-out noise exceeds the background noise by a factor of  $\sim 7.1$ , and that both these sources of noise exceed the uncertainty introduced by source photon statistics for all cases but the very brightest AGNs (none of which are present in this field). We find that we expect to be able to detect AGNs as faint as  $V = 19.6\ \text{mag}$  at  $S/N = 100$  in an hour. Adjusting for foreground extinction ( $A_V = 0.6$ ) and assuming a mean color  $B - V \approx 0.4$ , this corresponds to  $B = 19.4\ \text{mag}$  in an unreddened field. Koo & Kron (1988) find that the total surface density of AGNs is  $\sim 100\ \text{degree}^{-2}$  to a limiting magnitude  $B = 21.1\ \text{mag}$ . Thus, the surface density to  $B = 19.4\ \text{mag}$  is approximately  $9.5\ \text{degree}^{-2}$ . Assuming a field of view of  $7''.4$  and a correction factor of 0.8 for detector gaps and flaws gives an expected number of suitable targets

$$N_{\text{expected}} \approx 330.$$

Although this seems like a suitably large sample for an AGN variability study, we note the following:

1. As one approaches the faint end of the distribution (where one finds the great majority of the targets), *source confusion* might become a serious problem for such large images. The individual targets need to be examined carefully on high-quality images to make sure that the target can be photometrically distinguished from other nearby objects (mostly faint foreground stars) at low angular resolution.
2. As always in faint-object astronomy, the background must be measured accurately. A suitable number of “blank fields” must also be measured to determine the background level.

The calculation made above assumes a gain of unity, i.e., that  $1\ \text{ADU} = 1\ \text{e}^-$ . This presents a problem if the entire electron well depth is to be used for the bright objects and the number of bits in the A/D converter is small. For example, if the full well per pixel is  $5 \times 10^5\ \text{e}^-$  and a 14-bit A/D converter is used, then the required gain is  $5 \times 10^5 / 2^{14} \approx 30\ \text{e}^-$  per ADU. We will decrease this slightly to 25 so that the read-out noise is well sampled. We require that the digitization process not limit the signal-to-noise ratio at the faint end, i.e., the number of counts per read-out must exceed

$2S/N$ . For  $S/N = 100$ , we find that we are limited to  $V \lesssim 16.2$  mag. The expected number of AGNs in the field thus becomes very small (only about 10). High-quality well-sampled light curves for even a *very few* AGNs would be valuable, despite the loss of statistical information. However, it is in principle possible to overcome this limit by changing the gain in software for each local-area read, and this should be done for the fainter objects. Several other pixel-to-pixel changes can be programmed to increase  $S/N$  since the signal level in each pixel is known *a priori* to a fraction of a percent.

### 3.3. Target Selection

Because of its proximity to the Galactic plane, the proposed FRESIP field has not been well-surveyed for AGNs. A search of the major AGN catalogs (Véron-Cetty & Véron 1989; Hewitt & Burbidge 1987, 1989) reveals that there are *no* known AGNs in the FRESIP field, although there are several fairly bright AGNs within about  $15^\circ$  or so of the field center. Clearly the field will need to be surveyed in detail prior to launch to search for AGNs, as well as other sources. The AGNs can be isolated through multicolor imaging and/or objective prism spectroscopy, and the search strategy will depend to some extent on how deep one wishes to go. A prelaunch survey of the field will require significant lead time, and this should be taken into consideration in the early stages of project planning.

## 4. ALTERNATIVE DESIGNS

We have given further consideration to how some of the baseline parameters might be altered to enhance the AGN variability experiment, in part to emphasize the impact various trade-offs will have on faint-object secondary science. Since AGNs are faint sources, the quality of the observations is background-limited. Therefore, a significant improvement can be realized by better focusing of the telescope; since AGNs are all faint, saturation of targets is not a concern. (For a mission optimized for an AGN study, the brightest stars would need to be masked out, or detectors with effective anti-blooming characteristics would be required.) In order to enhance the performance of a telescope in the proposed orbit for AGN monitoring, we would recommend the following changes:

1. The telescope should be focused to optimize the contrast of the point sources relative to the background. The telescope should be able to operate at the diffraction limit.

2. Since we are now considering monitoring fainter objects, we will increase the individual integrations from 2.3 seconds to something like 10 minutes in order to increase  $S/N$ .
3. The selected field should be at higher Galactic latitude to reduce the effects of Galactic extinction; an unextinguished field will yield more than two times as many suitable targets per unit solid angle as the FRESIP field. From the point of view of AGN monitoring, more suitable fields are available in the FRESIP continuous viewing zone.

We note that in the background-limited regime, the highest throughput is attained by the image by matching the Airy disk to the pixel size. The full-width at zero intensity of the Airy disk is

$$\theta_A(\text{radians}) = \frac{2.44\lambda}{D},$$

where  $\lambda$  is the wavelength and  $D$  is the diameter of the primary mirror. The angular size of a pixel of size  $d$  for focal length  $F$  is  $\theta_{\text{pixel}} = d/F$ . To first approximation, the Airy disk should cover at least two pixels, i.e.,

$$\theta_A \geq 2\theta_{\text{pixel}}$$

which can then be rewritten as a restriction on the system focal ratio

$$f = \frac{F}{D} \geq \frac{d}{1.22\lambda}.$$

Selection of the pixel size is thus of great importance. We believe that a more realistic assumption about the pixel size is  $15\mu\text{m}$  rather than  $24\mu\text{m}$ . Optimal pixel sizes are basically a trade-off between the difficulty of fabricating small pixels on the one hand and the difficulty of producing high-quality large-format chips on the other. Our perception is, that for large-format chips, pixel sizes  $15\mu\text{m}$  and smaller are most likely to be available commercially over the next several years. Thus, for an optical diffraction-limited system with  $d = 15\mu\text{m}$  and  $\lambda \approx 0.5\mu\text{m}$ , we have  $f \gtrsim 25$ ! Obviously such a long focal length leads to an optical system more complicated than is being considered at the present time. Some simple considerations indicate that we can meet the performance criteria in §3.2 with a smaller telescope ( $D \approx 0.3\text{m}$ ) which has a wide field of view and is capable of fitting into a 2-m shroud. A wide-field telescope may require a refractive corrector, and this may in turn lead to reduction of the bandpass. A more detailed optical design needs to be carried out before any further assessment can be made.



## 5. CONCLUSIONS

Detailed monitoring of AGNs with FRESIP can provide well-sampled light curves for a large number of AGNs. Such data are *completely unprecedented* in this field, and will provide powerful new constraints on the origin of the UV/optical continuum in AGNs. The FRESIP baseline design will allow 1% photometry on sources brighter than  $V \approx 19.6$  mag, and we estimate that over 300 sources can be studied. We point out that digitization effects will have a significant negative impact on the faint limit and the number of detectable sources will decrease dramatically if a fixed gain setting (estimated to be nominally  $25\text{ e}^-$  per ADU) is used for all read-outs.

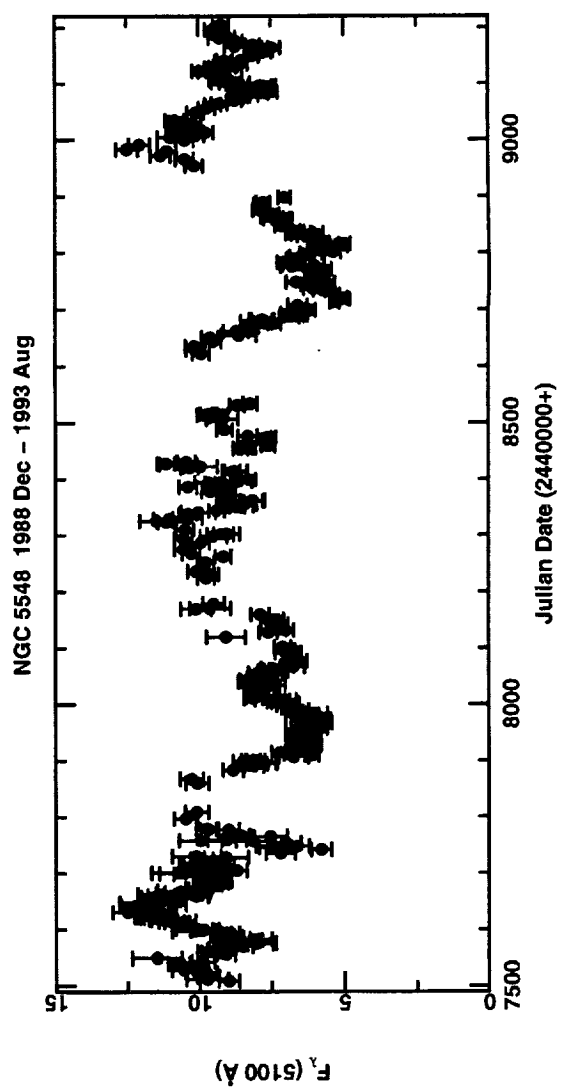
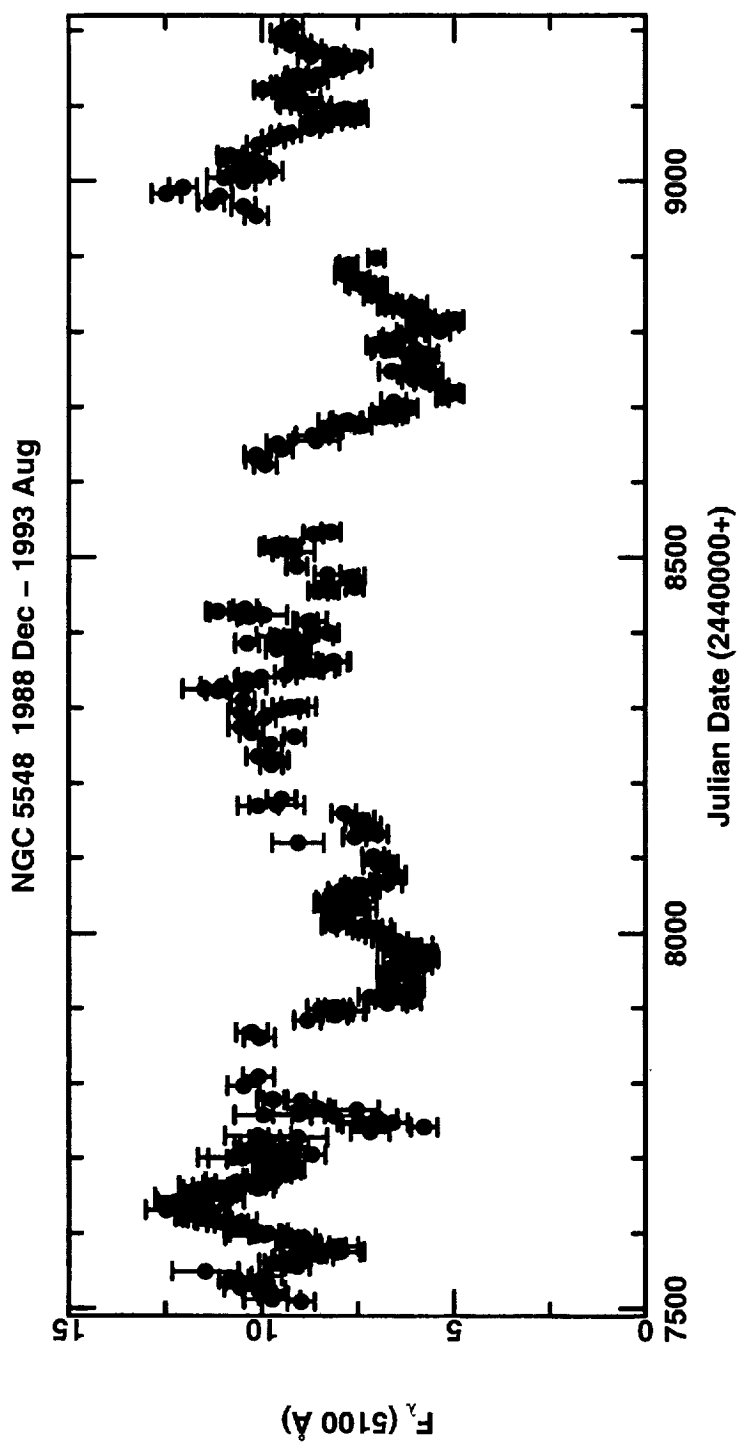
We note that the primary limitation to studying AGNs is background (sky and read-out noise) rather than source photon statistics, and thus better results can be achieved by increasing the source/background contrast with a focused telescope and by longer integrations. While we believe that it may be possible to achieve the AGN-monitoring science goals with a more compact and much less expensive telescope, the proposed FRESIP satellite affords an excellent opportunity to attain the required data at essentially zero cost as a secondary goal of a more complex mission.

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